# SURVEY OF THE RESEARCH OF ICT APPLICATIONS IN THE AEC INDUSTRY: A VIEW FROM TWO MAINSTREAM JOURNALS

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***ABSTRACT:*** *The application of information and communication technology (ICT) in the Architecture, Engineering and Construction (AEC) industry has attracted much attention by researchers in recent years. However, a comprehensive review is still missing from the existing literature. This paper aims to provide a comprehensive overview of the state-of-the-art research of ICT applications in the AEC industry. A total of 432 articles, published during 2011-2015 in two mainstream journals, namely Automation in Construction and Journal of Computing in Civil Engineering, are selected and analyzed. This review is conducted from three different views: 1) view of construction project lifecycle, aiming to investigate the distribution of research of ICT application in different stages; 2) view of ICT technologies, aiming to identify the popular ICTs in the AEC industry that researches focus on; and 3) view of ICT application areas, aiming to identify the areas in the AEC industry that ICTs are applied in. Throughout this review, the distribution of the research of ICT in four different stages (i.e., design stage, construction stage, operation & maintenance stage, and multistage) is firstly investigated. A total of 24 types of ICTs, categorized into 8 groups and 19 ICT application areas are then identified and analyzed. In additional, limitations of this review are also discussed.*

***KEYWORDS:*** *Information and communication technology (ICT), Architecture, engineering, and construction (AEC) industry, literature review*

## 1. INTRODUCTION

The Architecture, Engineering and Construction (AEC) industry is an extremely information-intensive and knowledge-based industry where stakeholders create, consume and communicate a large amount of information throughout the project lifecycle (Dave and Koskela, 2009). Information and Communication Technology (ICT) has been widely recognized as a significant solution to improve the productivity and efficiency of information generating, transmitting, processing and managing in the whole construction process (Kang et al., 2013; Samuelson and Björk, 2014). Its applications in the AEC industry have attracted much attention by researchers since the last decades in the 20$^{th}$ century and a large number of relevant research have been conducted (Xue et al., 2012; Lu et al., 2014).

In the large body of existing research, many emerging ICTs have been explored and discussed to address specific issues in the whole life cycle of various AEC projects. To make a comprehensive and meaningful understanding of the research status of ICT applications in the AEC industry, an in-depth literature review is in need and important. A number of literature reviews have been conducted and they can be categorized in two groups: 1) reviews focusing on summarizing the research progress of one or several specific ICTs applied in the AEC industry, such as Augmented Reality (AR) (Chi et al., 2013), RFID (Lu et al., 2011), Building Information Modelling (BIM) (Volk

et al., 2014), 3D/4D CAD (Park et al., 2011) and sensing technologies (Vähä et al., 2013); 2) reviews concentrating on ICT applications in specific domains of the AEC industry, such as review of digital design technologies used for construction safety (Zhou et al., 2012), IT applied for supporting collaborative work in construction projects (Xue et al., 2012), and digital ICTs used in procurement of construction projects (O. Ibem and Laryea, 2014). These studies provide ample specific views for understanding the research status of ICT uses in the AEC industry. However, a general and comprehensive view is still missing.

To fill this gap, this paper aims to provide a comprehensive overview of the state-of-the-art research on ICT applications in the AEC industry. More specifically, the objectives of this paper are: 1) to investigate the whole trend of the research on ICT applications in the AEC industry; 2) to identify key ICTs applied in the AEC industry and their key application areas; and 3) to brief the research trends of ICTs applications in the AEC industry. The rest parts of this paper are organized as follows: a clear scope definition of ICT discussed in this paper is given in Section 2; the research approach including qualified literature selection and review framework is described in Section 3; Section 4 presents detail study findings; and Section 5 concludes the paper.

## 2. ICT IN THE AEC INDUSTRY CONTEXT

A specific definition of the scope of ICT in the AEC industry context is required as a basis for this study. To achieve this goal, an attempt is made at reviewing the evolution of ICTs and different explanations in the literature. In a general context, Hamelink (1997) defined the ICTs as all those technologies that enable the handling of information and facilitate different forms of communication among human actors, between human beings and electronic systems, and among electronic systems. He explained that “digitization” is a common feature of ICTs. Hamelink (1997) further categorized ICTs into five groups: 1) capturing technologies for collecting and converting information into digital forms; 2) storage technologies for storing and retrieving information in digital forms; 3) processing technologies by creating systems and software applications that are required for the performance of digital ICTs; 4) communication technologies for transmitting information in digital forms; 5) display technologies for the display of digitized information.

In the AEC industry context, there is no specific and consistent definition of ICT. The explicit definition or scope of ICT is rarely discussed in relevant research even in some review studies. Based on a simple project process model, Froese (2005) discussed the roles of IT in construction projects. The main roles include: 1) individual tools or computer applications to implement project tasks; 2) communication technologies to convey the information; 3) IT systems to address systematic construction problems. Onyegiri et al. (2011) considered that ICT in construction can be “the interaction of meaning to reach a mutual understanding between a sender and a receiver via technology”, which focuses on the communication function of ICT. Adriaanse et al. (2010) defined the inter-organizational ICT in the AEC industry context as “a digital coordination and collaboration tool used for communicating and sharing project information between participating organizations in a construction project”. This definition emphasizes ICT’s role of providing collaborative platforms or tools for construction management. Many researchers adopt this definition although it is not given explicitly. For example, Xue et al. (2012) conducted a review focusing on the IT supported collaborative work in the AEC projects by using “IT”, “collaboration” and

their relevant terms as the keywords to filter targeted papers.

Based on above studies, we believe that ICTs in the AEC industry context have the following characteristics: 1) the ICTs focus on handling construction information in digital forms; 2) the ICTs play various roles including capturing construction information in digital forms, and storing, processing, communicating and displaying these pieces of digital information; 3) the ICTs can be applied on different levels including individual task level and organizational task level. This paper focuses on all the ICTs that have these basic characteristics.

# 3. METHODOLOGY

## 3.1 Journal selection

To acquire the articles related to the research of ICT applications in the AEC industry, the source of these papers, namely the relevant journals, should be selected. Two criteria are adopted in this paper to select these journals: (1) the journal shall be a peer-reviewed scholarly journal; (2) the journal shall have a core focus on the research of ICT applications in the AEC industry.

A similar journal search was performed by Lu et al. (2014) and 12 peer-reviewed journals were picked out. According to the scope of ICT defined in this paper, there are a large number of researches on ICT applications in the AEC industry published on these journals. In this preliminary study, two representative journals, namely Automation in Construction (AIC) and Journal of Computing in Civil Engineering (CCE), are firstly selected and analyzed. Both two journals are peer-reviewed and accepted as prominent and high-quality journals in the research of ICT applications in the AEC industry (Xue et al., 2012; Lu et al., 2014). For example, Lu et al. (2014) adopted AIC and CCE as partial data source to present an in-depth review of mainstream studies of ICT-supported AEC organizations. In addition, unlike some journals such as *Journal of Construction Engineering and Management* that has relatively weak relevance, AIC and CCE are highly relevant. Therefore, to some degree, analyzing the distribution of articles in these two journals is helpful to investigate the status of ICT application research in the whole AEC academic community.

## 3.2 Article retrieval

After the selection of journals, qualified articles need to be retrieved from these two journals. Using ICT to address a range of operational and managerial issues in the AEC industry has been started in earnest in the last three decades of the 20th century by researchers (Lu et al., 2014). However, considering the goal of this study, which is to investigate the state-of-the-art research status of ICT applications in the AEC industry, and the huge number of relevant papers published in the past time, this study selects the recent five years, namely 2011-2015, as the review period. In addition, the number of selected articles reached at 432 (the selection process is described below) and we believe this quantity is appropriate to achieve our research goal. More details about the cover of the two journals can be found in Table 1.

Generally, keyword searching in specific databases such as Scopus, Web of Science and Google Scholar is a common and effective article retrieving method for literature research. However, this method requires that the keywords can be enumerated with a limited list of terms. In our case, the definition of ICT adopted in this paper has a rather broad scope. It is really difficult to list complete terms to form appropriate keywords for literature search. A general keyword search-based approach would easily cause remarkable omitting of qualified papers in this situation.

In this paper, we search target articles manually, more specifically, complying with the following steps:

*Step 1: establish the inclusion and exclusion criteria*

These criteria are set based on the research scope of this paper. Articles would be included if they focus on the research, review or survey of the applications of ICTs (defined in this paper) in the AEC industry. Articles would be excluded if they: (1) focus on the research of ICT applications in other industries such as the manufacturing industry (e.g. ICTs application in the manufacture of construction equipment); (2) focus on ICTs themselves instead of their applications in the AEC industry (e.g., pure theoretical or technological development of ICTs); (3) focus on the pure mathematical algorithms or simulation methods development.

*Step 2: select articles from the selected journals*

Qualified articles are selected by logically checking their titles, keywords, and abstracts to judge whether the articles comply with the established inclusion and exclusion criteria.

Following the two steps, a total of 432 articles have been retrieved from 1181 articles published in the two journals in the period of 2011-2015. The distribution of selected articles in different journals is shown in table 1. The percentages of selected articles in AIC and CCE are almost 40% and 30% respectively, which shows the two journals are highly relevant to the research of ICT applications in the AEC industry.

Table 1: Overview of journals and selected papers

| Journal | Issue covered | Number of total articles | Number of selected articles | Percentage of selected articles |
|---|---|---|---|---|
| AIC | 20(1), 2011 – 60, 2015 | 807 | 321 | 40% |
| CCE | 25(1), 2011 – 29(6), 2015 | 374 | 111 | 30% |
| Total | - | 1181 | 432 | 37% |

## 3.3 Framework of review

An analysis framework is established to efficiently and effectively achieve the research objectives proposed above. In the framework, these selected articles are analyzed through three different views, namely view of ICT

technology, view of ICT application area, and view of construction project lifecycle.

In the view of construction project lifecycle, all the selected articles are categorized into certain stages to investigate the research status of ICT applications in different construction stages. To make the classification simple and clear, in this paper, we set four groups to categorize these articles, including design stage, construction stage, operation and maintenance (O&M) stage, and multistage. The design stage covers the all the pre-construction activities such as planning, feasibility study and design. In addition to the on-site construction activities, off-site activities such as material procurement & transportation and component prefabrication also belong to construction stage. Other than operation and maintenance of facilities, the O&M stage also covers the demolition of facilities. Multistage applies to the situation in which the application of ICTs involves more than one single stage. The articles that cannot be classified into a certain stage also fall into this stage.

In the view of ICT technologies, all the articles are categorized based on the specific ICT technologies that the articles focus on. This view aims to investigate ICT technologies and their distributions in the state-of-the-art research in the AEC industry.

In the view of ICT application areas, the key application areas of ICTs are firstly identified from the articles. For each application area, the popular ICT technologies are further discussed.

# 4. FINDINGS AND DISCUSSION

## 4.1 Overview

The number of selected articles on ICT published annually in two journals is depicted in Table.2. From 2011 to 2015, the total number of articles published per year keeps a remarkable increase on the whole. Regarding to the two specific journals, the number of articles published annually in AIC shows the same trend with the total number, while the articles published annually in CCE keep a slow but stable growth from the year of 2011 to 2015. In addition, the articles published in AIC is much more than those published in CCE. As a whole, these trends show that the interests and effort on the research of ICT applications in the AEC industry keep at a high level in the recent 5 years.

Table 2: The number of articles published during 2011-2015

| Journal | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|
| AIC | 48 | 63 | 82 | 57 | 71 |
| CCE | 13 | 22 | 23 | 22 | 31 |
| Total | 61 | 85 | 105 | 79 | 102 |

## 4.2 View of construction project lifecycle

In the view of construction project lifecycle, all the selected articles are categorized into 4 groups according to the certain stage that they focus on. The proportions of articles distributed in each stage are shown in Fig. 1. It is clear to find that the articles show a similar distribution in two journals: the articles focusing on construction stage account for the largest percentage (43% for AIC and 46% for CCE), the articles focusing on O&M stage and multistage come to the 2nd and 3rd place respectively, and the proportions of articles related to the design stage in two journals are lowest (only 11% for AIC and 4% for CCE).

Fig. 2 shows the trends of the annual percentages of all selected articles in different stages from 2011 to 2015. As a whole, the proportion of articles related to O&M stage increases significantly from 15% in 2011 to 35% in 2015. However, the figure related to construction stage falls remarkably from 50% in 2011 to 35% in 2015. To some degree, this two trends show that researchers give more attention to explore the application of ICTs in the O&M stage. Although there is some fluctuation during 2011-2015, the proportions of articles focusing on design stage and multistage remain stable at the value of 10% and 22% respectively.

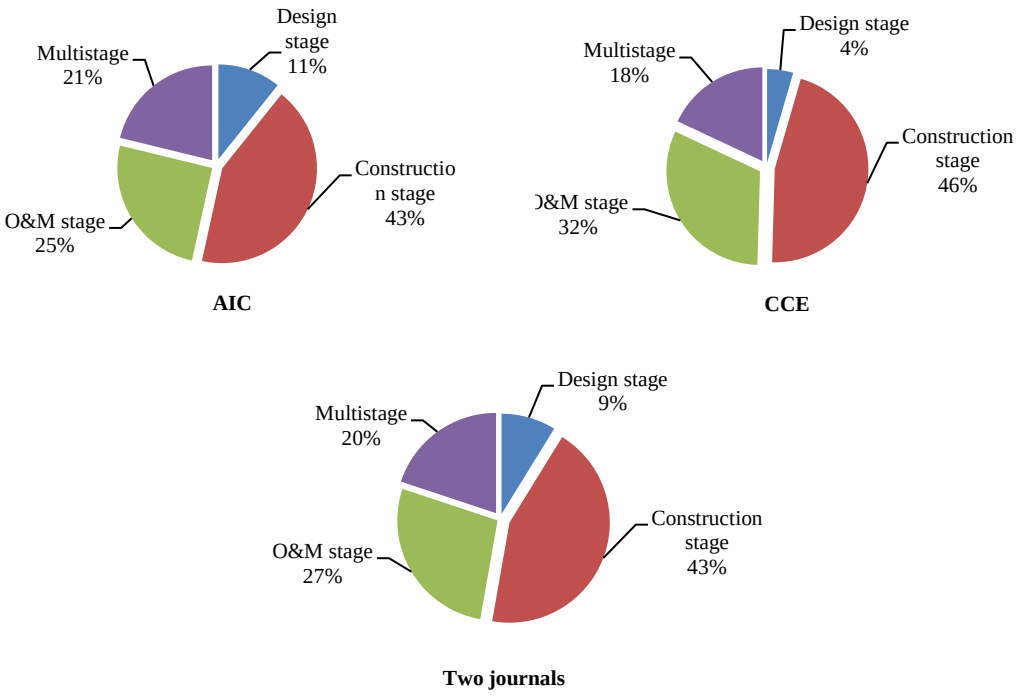


Fig. 1: The distribution of articles in different stages

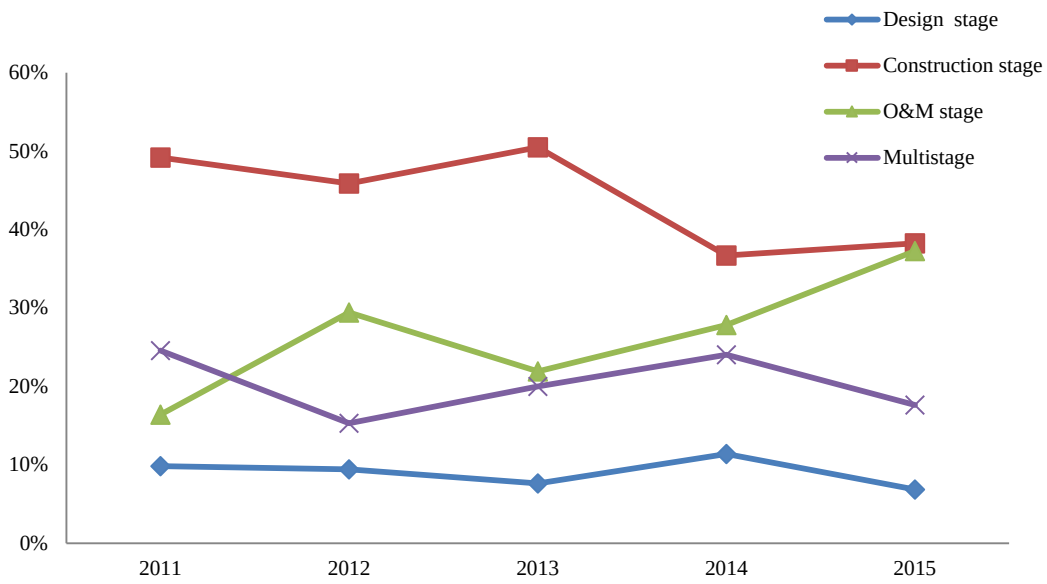


Fig. 2: The annual percentages of articles in different stages from 2011 to 2015

## 4.3 View of ICT technologies

According to the specific ICTs that the selected articles focus on, a total of 24 types of ICTs, categorized into 8 groups, are identified as shown in Table 3. In this paper, the type of ICT into which one article is classified depends on what ICT the article focuses on instead of what ICTs the article involves with. For example, the article "Real-time safety early warning system for cross passage construction in Yangtze Riverbed Metro Tunnel based on the internet of things" (Ding et al., 2013) focuses on the technology of Internet of Things (IoT) but also involves with other sensing technologies such as RFID and FBG sensor. This article is only counted as one paper in IoT. Also, it is worth to note that one article may equally focus on several ICTs. Then this article would be counted as one paper in all the relevant ICTs repeatedly. For example, in the article entitled "Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services" (Karan etal., 2015), BIM, GIS and Semantic Web are the three core ICTs studied in this article. Therefore, this article would be categorized into the type of BIM, GIS and Semantic Web separately. In addition, articles that focus on complicated and integrated information system, or the survey or review of ICT applications in the AEC industry would fall into the group of "Integrated or general ICTs" in the Table.3.

Table.3 shows that, according to the statistics of two journals, sensing technologies and product modeling technologies are the two groups of ICTs in the AEC industry that researchers are most interested in. On the specific ICT level, BIM (121), image processing (53), laser scanning (42), Augmented Reality, or AR (27) and RFID (24) are the top five ICTs that existing studies focus on. As the most popular ICT in the AEC industry, BIM are applied or studied in almost all the application areas identified in this paper. As a whole, BIM based collaboration platforms

(especially real-time or near real-time collaboration platforms), function extension and interoperability improvement with downstream applications, and more efficient and effective information processing (especially information extraction and visualization) mechanisms are the three major topics of BIM. In the areas of construction activities and progress monitoring, construction quality monitoring, defect detection and 3D reconstruction of as-built environment, image processing technologies receive increasing attention because of their low cost and flexibility of equipment. The images can be general photos, general videos and specific images such as 3D thermography. As a powerful non-contact data capturing technique, laser scanning (LiDAR/LADAR) has similar application areas with image processing in the AEC industry. Generally, this kind of technologies is more accurate but also more expensive than image processing technologies. AR, a state-of-the-art technology for superimposing information onto the real world object, has been studied to address many construction issues such as a lack of information for construction field operators and poor communications between project participants (Chi et al., 2013). The application of RFID in the AEC industry has been widely studied. Most of these studies related to RFID applications (16 out of 24) reviewed in this paper focus on construction stage, more specifically, the resource (e.g., construction materials and equipment) and workers' location tracking on construction site.

## 4.4 View of ICT application areas

A total of nineteen ICT application areas are identified and all the selected articles are categorized into these areas, as shown in Table.4. The number of articles distributed in the top ten application areas reaches at 376, which accounts for 87% of the total articles. The left nine application areas are discussed in only 58 articles in total. In the following parts of this section, we mainly focus on investigating the popular ICTs applied in the top ten application areas.

In the application area of safety monitoring and management, ICTs play an important role to achieve a real-time (or near real-time) and visual safety monitoring and risk warning. This area can be further divided into three sub areas, as follows: 1) construction safety monitoring, which focuses on the safety of workers, materials and construction activities; 2) construction equipment safety monitoring, which pays attention to the safety monitoring of construction equipment, especially heavy construction equipment such as cranes and excavators; and 3) disaster and emergency responding, which aims to put forward safer and more efficient approaches to respond natural disasters (e.g. earthquake) and emergencies (e.g. fire). Highly focused areas of the ICTs include BIM, sensing technologies (e.g., Sensor, RFID, GIS, GPS), networking and communicating technologies (e.g. WSN, UWB), and visualization technologies.

Table.3: The number of articles focusing on different ICT technologies

| ICT technologies | Number of articles | | |
|---|---|---|---|
| | AIC | CCE | Total |
| **1. Product modeling** | | | |
| (1) BIM (e.g., BIM, openBIM, BIM server, cloud BIM) | 113 | 8 | 121 |
| (2) CAD | 13 | 4 | 17 |
| (3) Others | 10 | 1 | 11 |
| **2. Sensing and spatial technologies** | | | |
| (1) Image processing | 27 | 26 | 53 |
| (2) Laser scanning | 32 | 10 | 42 |
| (3) RFID (Radio-Frequency Identification) | 20 | 4 | 24 |
| (4) Spatial analysis technologies | | | |
| GIS (Geographic Information System) | 12 | 9 | 21 |
| GPS (Global Positioning System) / GNS (Global Navigation Satellite) | 7 | 1 | 8 |
| (6) Ultrasound scanning | 2 | | 2 |
| (7) Others | 19 | 7 | 26 |
| **3. Networking and communicating technologies** | | | |
| (1) Internet based Web (e.g., Email, e-business, agent system, P2P network, Social Networking Services (SNS)) | 20 | 3 | 23 |
| (2) Wireless Local Area Network (e.g., ZigBee, UWB (Ultra-Wide band)) | 12 | 1 | 13 |
| (3) Sensor Network (e.g., Wireless Sensor Network (WSN), Ubiquitous Sensor Networks (USN), IoT(Internet of Things)) | 6 | 2 | 8 |
| **4. Knowledge modelling** | | | |
| (1) Ontology | 1 | 4 | 5 |
| (2) Semantic Web | 18 | | 18 |
| **5. Data management and analysis** | | | |
| (1) Database | 5 | 5 | 10 |
| (2) Data warehouse | 2 | 1 | 3 |
| (3) Data mining | 6 | 1 | 7 |
| (4) Data fusion | | 3 | 3 |
| **6. Advanced computing (Cloud/Mobile/Distributed computing)** | **9** | **2** | **11** |
| **7. Visualization technologies** | | | |
| (1) AR (Augmented Reality) | 19 | 8 | 27 |

| | | | |
|---|---|---|---|
| (2) VR (Virtual Reality) | 10 | 5 | 15 |
| (3) Others | 12 | 3 | 15 |
| **8. Integrated or general ICTs** | **23** | **5** | **28** |

Table.4: The number of articles in different ICT application areas

| ICT application areas | Number of articles | | |
|---|---|---|---|
| | AIC | CCE | Total |
| Safety monitoring and management | 52 | 18 | 70 |
| Construction process monitoring | 51 | 18 | 69 |
| Sustainable construction | 31 | 7 | 38 |
| ICT adoption survey and assessment | 33 | 2 | 35 |
| Collaboration platforms and management systems | 26 | 8 | 34 |
| Construction quality monitoring and defect detection | 22 | 12 | 34 |
| As-built facility and environment modeling | 21 | 8 | 29 |
| Facility management and maintenance systems | 15 | 8 | 23 |
| Information retrieval and visualization | 10 | 11 | 21 |
| Construction planning and scheduling | 14 | 5 | 19 |
| Building design supporting | 10 | 2 | 12 |
| Construction cost management | 9 | 2 | 11 |
| Automated compliance checking | 9 | - | 9 |
| Worker training and student education | 4 | 3 | 7 |
| Construction data and document management | 4 | 1 | 5 |
| Construction activities simulation | 2 | 2 | 4 |
| Building space-use analysis | 4 | - | 4 |
| Construction product information searching | 2 | 1 | 3 |
| Construction component prefabrication supporting | 1 | 1 | 2 |

In this paper, construction process monitoring consists of two sub areas: construction activity monitoring, and resource tracking and locating. In both areas, researchers focus on developing real-time, visual and automatic approaches or systems to monitor the construction activities or track resources for the various purposes such as recording construction progress, evaluating construction performance and conducting schedule management. In this area, a wide range of ICTs such as BIM, networking and communicating technologies (e.g., wireless network and sensor network), sensing technologies (e.g., laser scanning and image processing) are integrated. Similar with

the area of construction process monitoring, other two areas, namely construction quality monitoring & defect detection, and as-built facility & environment modeling heavily rely on sensing technologies (e.g., laser scanning and image processing) to capture data.

The adverse impact of construction activities on environment and much carbon emission caused by building energy consumption have become a significant topic. Most of the relevant articles focus on the design, assessment, and operation monitoring of energy efficient buildings. Important ICTs involve BIM, sensing technologies and data mining.

In application areas of ICT adoption survey and assessment, the discussion of the benefits and hindrances of ICTs (especially BIM) adoption in the AEC industry has received an increasing attention. For example, a number of studies have been conducted to investigate the BIM implementation in a construction project lifecycle in different countries, to examine the driving factors of BIM adoption in design organizations, and analyze the cost and benefits of BIM adoption in construction projects.

Both in the application area of collaboration platforms and management systems, and facility management and maintenance systems, BIM, CAD, AR and VR are the most frequently mentioned ICTs used to develop specific collaborative work platforms and information management systems. A systematic and detailed review of ICT abled collaborative work in construction projects can be found in Lu et al. (2014).

In this paper, information retrieval and visualization refers to partial model information retrieval and 3D model visualization. Most of the research discussed in this paper focus on the BIM (especially IFC BIM) based partial building model information query. Regarding the model visualization, BIM, AR, VR and the integration of BIM with other visualization technologies are the major technologies. A number of articles focus on the automated generation of various types of construction plans and schedules as well as efficient visualization of this information. The involved ICTs include BIM, CAD, GIS and semantic web.

## 5. CONCLUSION

A total of 432 articles, published during 2011-2015 in two journals, namely Automation in Construction and Journal of Computing in Civil Engineering, have been selected and reviewed in this paper. This review aims to investigate the research of ICT applications in the AEC industry from three different perspectives: view of construction project lifecycle, view of ICT technologies and view of ICT application areas. The major findings from this review are summarized as follows:

- From the view of construction project lifecycle, construction stage and O&M stage are the top two stages that the research of ICT applications in the AEC industry focuses on. During 2011-2015, the proportion of the articles related to O&M stage increases significantly while the figure related to construction stage falls remarkably.
- From the view of ICT technologies, 24 types of ICTs categorized into 8 groups that researchers focus on are identified. BIM, image processing, laser scanning, AR and RFID are the top 5 ICTs that the selected articles

focus on. The main application areas of the five ICTs are analyzed.

- From the view of ICT application areas, 19 ICT application areas in the AEC industry that researchers focus on are identified. The top 10 application areas contains 87% of all the selected articles and the major ICTs involved in these application areas are analyzed.

We acknowledge that one major limitation of this paper is that the scope of this review is limited to the two journals, although a total of 432 articles are included. Therefore, the generality of the conclusion made in this paper need to be further validated. A number of other influential related journals, such as *Advanced Engineering Informatics*, *Journal of Information Technology in Construction* and *Journal of Construction Engineering and Management,* shall also be taken into consideration as future work for further data collection and more comprehensive data analysis. In addition, the current classification systems for ICT technologies and their application areas may be not structured, unambiguous and completed, we will continue to improve them in future after analyzing more data.

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